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13. ABSTRACT (Maximum 200 words)

EFFICIENT AND ACCURATE PREDICTION OF NONLINEAR AIRLOADS IS NECESSARY FOR DESIGNING THE AIRCRAFT IN THE TRANSONIC REGIME. THE FLOW IN THE THE TRANSONIC REGIME IS A MIXTURE OF SUBSONIC AND SUPERSONIC FLOW WITH EMBEDDED SHOCKS. THE GOVERNING TRANSONIC AERODYNAMIC EQUATIONS ARE HIGHLY NONLINEAR AND ARE COMPUTATIONALLY EXPENSIVE TO SOLVE. THE AERODYNAMIC NONLINEARITIES HAVE A SIGNIFICANT IMPACT ON THE AEROELASTIC QUANTITIES AND ON THE RESULTING DESIGNS, HENCE THEY HAVE TO BE TAKEN INTO ACCOUNT. FULL FLEDGED EULER OR NAVIER-STOKES SOLUTION METHODS CANNOT BE USED IN THE PRELIMINARY DESIGN DUE TO THE ENORMOUS COST INVOLVED.

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Final Report

Computational Mechanics Approach for Multidisciplinary Nonlinear Sensitivity Analysis

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Objectives:

The objective of this research work is to develop a method for aeroelastic sensitivity analysis of aircraft in the transonic regime, which should be relevant to the preliminary design. Appropriate physical models that represent the structure and aerodynamics in the transonic regime are developed. Steady aeroelastic performance is computed using nonlinear aerodynamic load predictions for suitably accounting the high dynamic pressures and sonic shocks. In this research, steady aeroelastic performance such as the control effectiveness is computed iteratively and its sensitivity with respect to the structural sizes (skin, spar, and rib thickness), is determined. Analytical sensitivities provide the fundamental understanding of the steady aeroelastic behavior with respect to crucial parameters that the designer could modify to improve the vehicle performance. The sensitivity studies could be used to increase the range and maneuverability, and decrease the drag on the aircraft system. Furthermore, the flexibility of the structure could be used as an asset to improve the aeroelastic performance. This procedure could be extended to other aeroelastic performance measures such as lift effectiveness, divergence, and flutter. In addition, for rapid execution of computational experiments in the transonic regime, nonlinear approximation concepts for modeling the aerodynamic pressures and the aeroelastic response functions are developed. As an outcome of this research, a scientific approach for conducting the sensitivity analysis in the transonic regime is available, further reducing the frequent wind tunnel experiments and flight-testing.

Status of effort:

Efficient and accurate prediction of nonlinear airloads is necessary for designing the aircraft in the transonic regime. The flow in the transonic regime is a mixture of subsonic and supersonic flow with embedded shocks. The governing transonic aerodynamic equations are highly nonlinear and are computationally expensive to solve. The aerodynamic nonlinearities have a significant impact on the aeroelastic quantities and on the resulting designs, hence they have to be taken into account. Full fledged Euler or Navier-Stokes solution methods cannot be used in the preliminary design due to the enormous cost involved.

As a precursor to the preliminary design, many optimization algorithms need analytical gradients of performance measures for computing the search directions. In this research, two distinct approaches are developed for transonic design. The first one is the derivation of analytical gradient information of aeroelastic measures from the equilibrium equations. The second one is the non-gradient based approach using the design of experiments.

Gradient method

Nonlinear sensitivity analysis is one of the most computationally intensive calculations in the preliminary design of an aircraft. It is the main obstacle for the use of

nonlinear aerodynamics in the design. However, the maturity and availability of aerodynamic analysis programs make it possible to create an aeroelastic design in the transonic regime if an efficient sensitivity analysis method is provided.

Therefore, the research begins with the selection of the aerodynamic analysis tools, which should be a trade-off between accuracy and efficiency. CAP-TSD, Computational Aeroelasticity Program-Transonic Small Disturbance, is selected as the aerodynamic analysis tool. Previous researches show that CAP-TSD fulfilled efficiency and accuracy requirements for the preliminary design. Besides, CAP-TSD is one of the fastest codes that can take into account the sonic shocks. From the simulations conducted on fighter wing configurations, it has been shown that there are significant differences between the CAP-TSD linear analysis and the nonlinear analysis. The pressure distributions are completely different. For the linear analysis, the pressure increased at the hinge line and the leading edge; but for the nonlinear case, there is a sonic shock that appears across the wing and it developed span wise. The magnitudes of the pressure is also different, the nonlinear analysis has a larger pressure than the linear analysis. Therefore, the nonlinear analysis is necessary in the transonic regime.

Although a potential theory was selected for the aerodynamic analysis, the sensitivity analysis of the static aeroelastic performance is still difficult because of the complexity introduced by implicitly coupled elastic and aerodynamic equations and the complicated and highly nonlinear aerodynamic equations. Since the nonlinear partial differential equation has to be solved using an iterative procedure, sensitivity analysis, which needs to evaluate the first derivatives with respect to the structural design variables, is more complex than the original nonlinear partial differential equation.

First, analytical sensitivity analysis is selected to perform the sensitivity analysis because of its accuracy and efficiency. Two approaches are explored in this research. The Approach I differentiated the equilibrium equations after the factorization. Instead of directly finding the sensitivity of the structural design variables, the aeroelastic and aerodynamic equations are solved alternatively for the sensitivity of the increment of the velocity potential with respect to the generalized stiffness at each time step. Then the sensitivities with the structural design variables are calculated using the chain rule of differentiation. The Approach II differentiated the equilibrium equation before the factorization, but at the converged solution of CAP-TSD analysis, the resulting partial differential is linear because of the original TSD equation is a quadratic partial differential equation. The Approach II does not require solving the sensitivity equation at each time step and it only needs to be solved at the converged solution of CAP-TSD analysis. Approach II has considerable saving in computational effort, but all the available sophisticated system equation solvers could not be used since the sensitivity matrices do not have symmetry or bandedness.

Non-gradient method

The second approach for design is the use of non-gradient methods. These methods have gained popularity in the last few years due to the availability of powerful workstations at lower prices. In structural optimization, when the sensitivity information is not available and the function evaluation is computationally expensive, using the response surface method for approximating the dependent variable as a function of independent variables is a popular choice. Careful application of the response surface method by judicious selection of design points, independent variables, and ranges of independent variables leads to a fairly accurate approximation. In this work, control surface effectiveness variation with respect to the statistically significant structural variables (skins, spars, ribs, and posts) is approximated using the response surface method. The statistically significant design variables are found using the fractional factorial design and the design points for response surface approximation are determined using the D-Optimality criteria. Multidisciplinary optimization for minimum weight, with control effectiveness, stress, displacement, and frequency constraints, is performed.

Accomplishments/New Findings:

In the first approach, the analytical sensitivities are derived and compared with the finite difference scheme with various step sizes. The performance measures such as the aerodynamic pressures at selected locations of a wing, rolling moment and lift are compared. The sensitivity of the velocity potential with respect to the generalized displacement is an essential step for the calculation of the sensitivity of aerodynamic loads with respect to the generalized displacement. After calculating the sensitivity of the velocity potential with respect to the generalized displacement, the sensitivity of the aerodynamic pressure is calculated. The sensitivity of the total lift and total pitching moment with respect to the generalized displacement are calculated from the sensitivity of the aerodynamic pressure with respect to the generalized displacement. The results obtained from the finite difference and analytical methods have a difference below 0.1% for the box wing model at Mach 0.94. The sensitivity of total lift and pitching moment with the first generalized displacement is two orders of magnitude less than that of the second and fourth generalized displacement; hence for the box wing model, the first bending motion has less influence on the flow field than the twisting mode (mode 2 and mode 4). The analytical derivations proved accurate for this demonstration problem and work is in progress for an Intermediate Complexity Wing (ICW), which is a significantly complex problem demanding efficient equation solvers for sensitivity calculation.

The response surface method was applied along with multidisciplinary requirements of a wing structure, and the design results are obtained using linear and nonlinear aerodynamics. Consideration of nonlinear aerodynamics is a necessary part of the preliminary design because the results obtained with the linear theory are extremely non-conservative. The linear aerodynamics predicted significantly higher performance than the actual value obtained from nonlinear aerodynamics. Roll performance improvements using the response surface methodology is a good practical choice in the

case of less number of design variables, lack of sensitivity information, and also when the simulations are expensive. The limitation of using TSD theory is that it is not applicable for extreme flight conditions involving high nonlinearities.

Personnel Supported:

The following Graduate Research Assistants were supported at various times during the grant period: Dr. Guosong Li, Mr. Henglin Wang, Mr. Somu Aryasomayajula, Mr. Chakradhar Byreddy, and Mr. Srinivasan Janardhan. The principal investigator was partially supported during the award period.

Publications:

Aryasomayajula, S., Wang, H., Grandhi, R., and Eastep, F., "Multidisciplinary Design of Vehicle Structures with Improved Roll Maneuverability in Transonic Regime", accepted for publication in Journal of Aircraft, AIAA (2000).

Interactions/transitions:

The principal investigator and the graduate students very closely interacted with the Air Force Research Lab engineers at Wright Patterson Air Force Base. This task compliments the research work that is being accomplished at AFRL by Dr. Phil Beran, Major Brian Sanders, Dr. Frank Eastep, Dr. N.S. Khot, and Dr. Chris Pettit. Several meetings and technical exchanges took place during this reporting period.

Participation/presentation at meetings, conferences, seminars, etc.

The principal investigator presented the research work at the AFOSR annual meetings held in Annapolis, MD, Dayton, OH, and Columbus, OH. Also, the P.I. gave a detailed presentation to Dr. Daniel Segalman, Program Manager in September 2000.

New discoveries, inventions, or patent disclosures: None

Honors/Awards: None

Markings: None